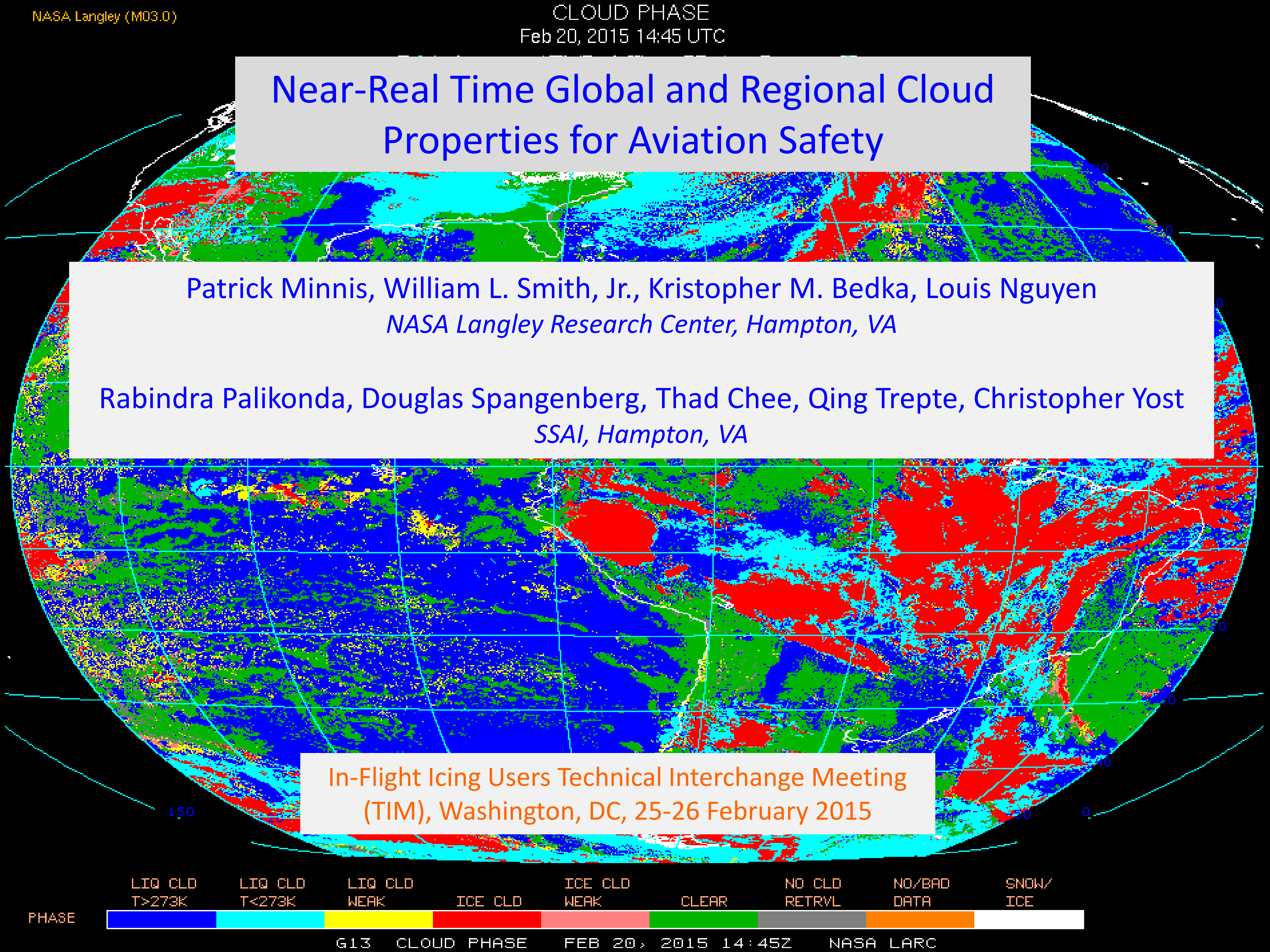
# Near-Real Time Global and Regional Cloud Properties for Aviation Safety

Patrick Minnis, William L. Smith, Jr., Kristopher M. Bedka, Louis Nguyen
*NASA Langley Research Center, Hampton, VA*

Rabindra Palikonda, Douglas Spangenberg, Thad Chee, Qing Trepte, Christopher Yost
*SSAI, Hampton, VA*

In-Flight Icing Users Technical Interchange Meeting (TIM), Washington, DC, 25-26 February 2015



# OBJECTIVES & APPLICATIONS

• Produce well-characterized consistent regional & global cloud and surface property datasets at all time & space scales

- use intercalibrated data
- use consistent algorithm as much as possible
- analyze data in *real time with minimal lag times*
- validate data as much as possible using independent measures
- improve as state of the art advances
- use satellites needed to cover variety of domains
    - LEO: MODIS, VIIRS, & AVHRR
    - GEO: GOES, Meteosat, MTSAT, FY-2, COMS
    - future: INSAT, Himiwari-8 & GOES-R

• Work with researchers and operations to use data for weather research & applications

- nowcasting => icing, HIWC, severe storms
- NWP model assimilation: work on all time and space scales
    - *global, continental, and regional*

# Standard Cloud/Radiation Parameters

## Standard, Single-Layer VISST/SIST

| | |
|---|---|
| **0.65**, 1.2, 1.6, 2.1 µm Reflectances | **Cloud** |
| **3.7**, **6.7, 10.8** µm Temp | **Mask, Phase** |
| 12 or 13.3 µm Temp | **Optical Depth**, IR emissivity |
| Broadband Albedo | **Droplet**/Xtal effective radius |
| Broadband OLR | **Liquid/Ice Water Path** |
| Clear-sky Skin Temperature | **Effective Temp**, height, pressure |
| **Icing Potential** | **Top**/ Bottom Pressure |
| Pixel Lat, Lon | **Top**/ **Bottom Height** |
| Pixel SZA, VZA, RAZ | **Overshooting top (OT)** |

- Primary channels: 0.65, 3.7, 10.8, 12.0 µm
  - *Minnis et al., TGRS, 2011*
  - lapse rates from *Sun-Mack et al (2014)*
- Secondary channels for mask & snow retrievals
  - 1.38, 1.2, 1.6, 2.1 µm (*not on AVHRR or most GEOs*)
  - 6.7, 13.3 µm (*not on AVHRR, VIIRS*)
    - *Minnis et al. AMS, 2010*

# Additional Cloud Parameters

## MODIS, VIIRS; soon: Himiwari-8 & GOES-R

| New Size Retrievals |
|---|
| Water droplet eff radius (1.24 μm) |
| Ice effective radius (1.24 μm) |
| Water droplet CER(2.1, 1.6 μm) |
| Ice CER (2.1, 1.6 μm) |

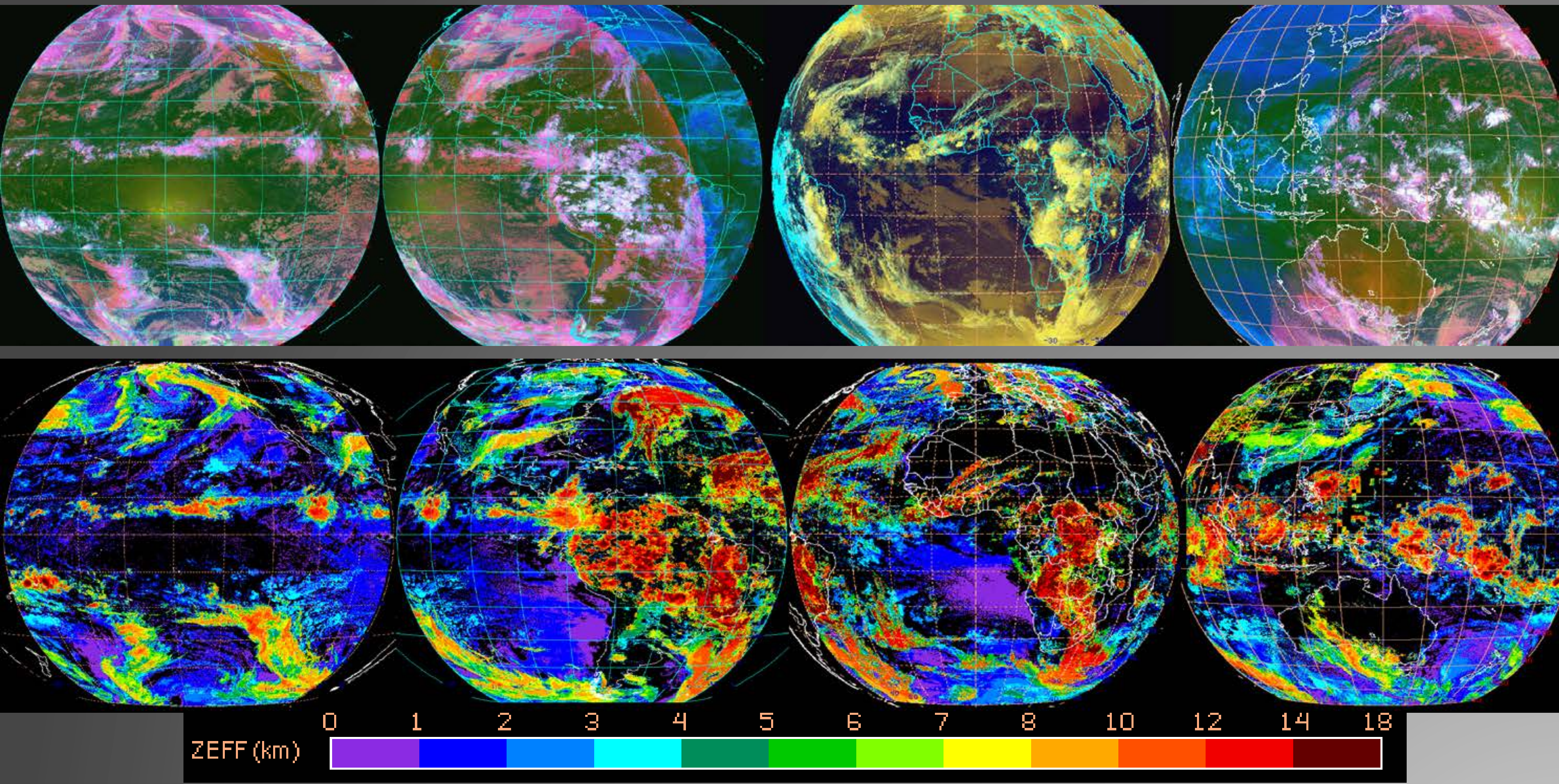
| CO2 Slicing |
|---|
| Cloud Top Pressure |
| Cloud Top Temperature |
| Cloud Top Height |
| IR Emissivity |

| Multilayer Cloud Retrieval | ( Ice Over Water ) |
|---|---|
| Multilayer Identification (GOES and Meteosat also) | |
| Upper Layer (Ice Clouds) | Lower Layer (Water Clouds) |
| Cloud Top Pressure | Cloud Top Pressure |
| Cloud Top Temperature | Cloud Top Temperature |
| Cloud Top Height | Cloud Top Height |
| Cloud Visible Optical Depth | Cloud Visible Optical Depth |
| Ice Effective Radius (3.7 μm) | Water Droplet Radius (3.7 μm) |
| Ice Effective Radius (2.1 μm) | Water Droplet Radius (2.1 μm) |

# GEO Retrievals, Hourly

2100 UTC, 12 November 2014, Cloud Effective Height

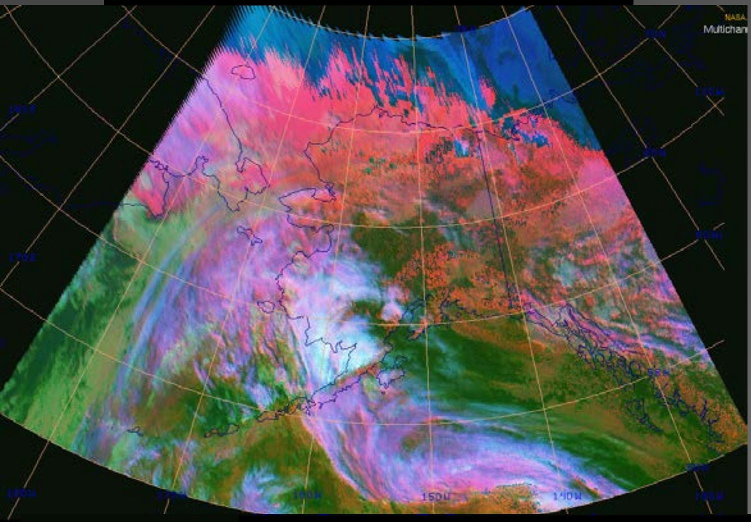
GOES-W GOES-E Meteosat MTSAT



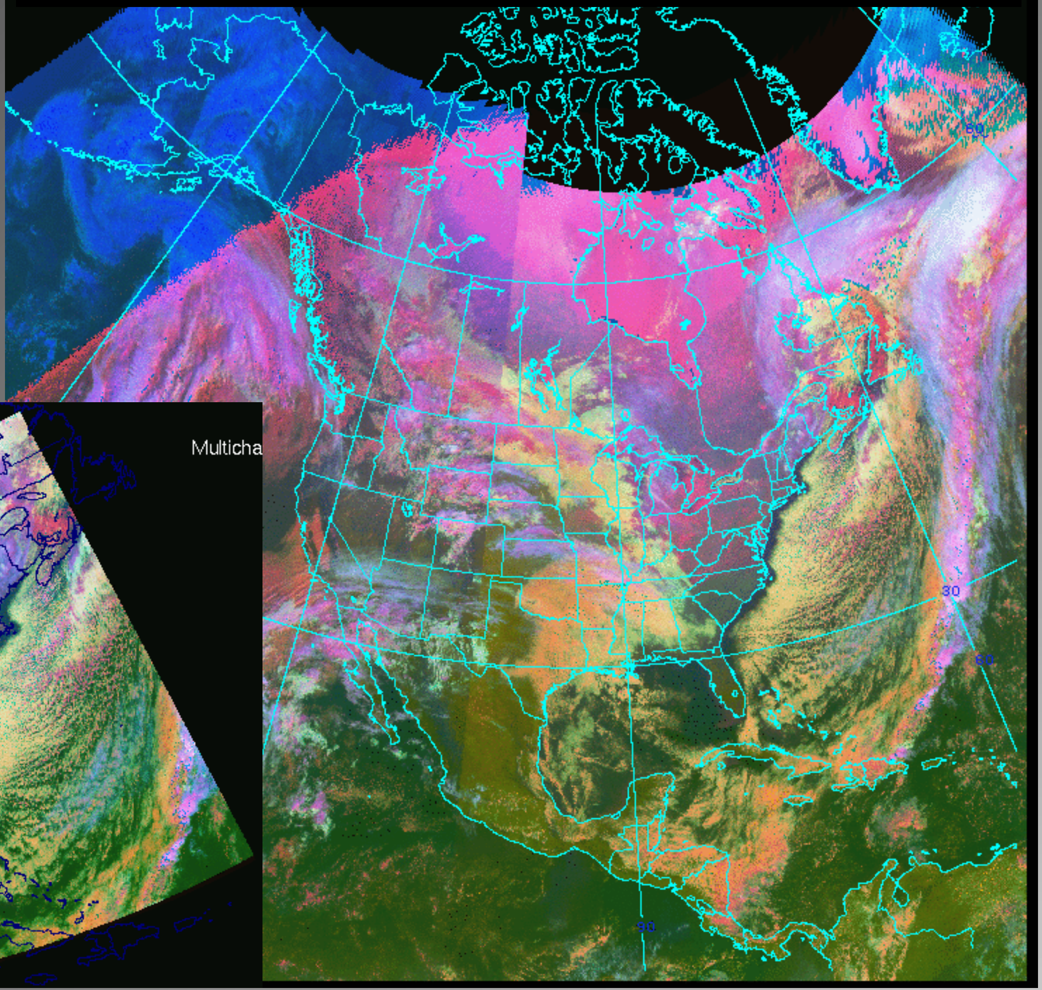

- Cloud properties computed each hour for each satellite
- 30° longitudinal gap over India (Indian Gap) to be closed in 2015
- Many other domains and time (15 – 30 min) and space (full res) scales

# Regional Domains

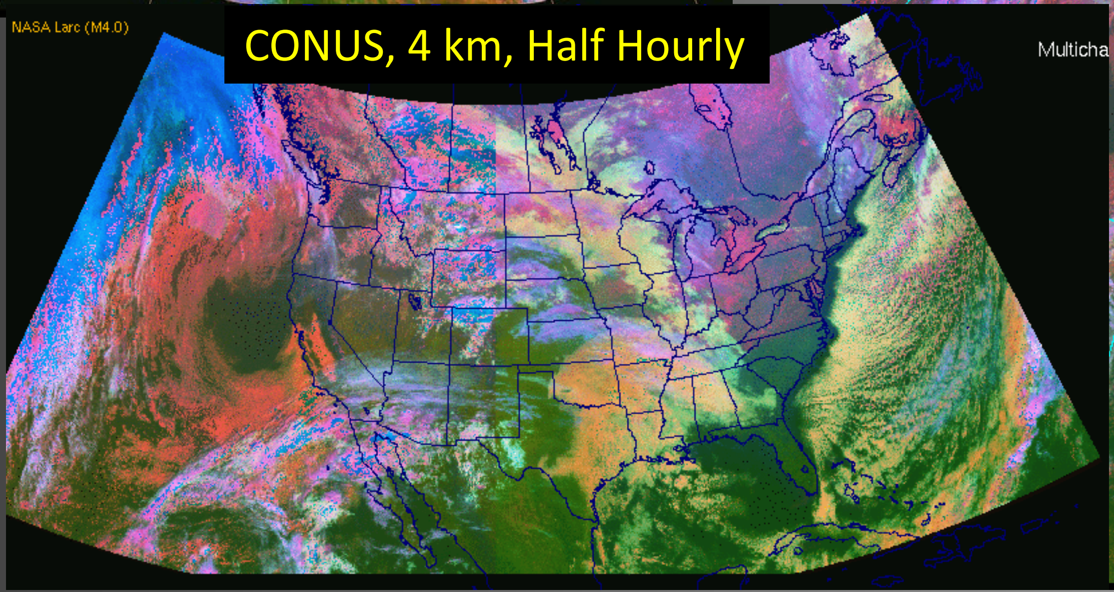
Alaska, 4 km, Half Hourly



North America (Rapid Refresh), 8 km, Half Hourly



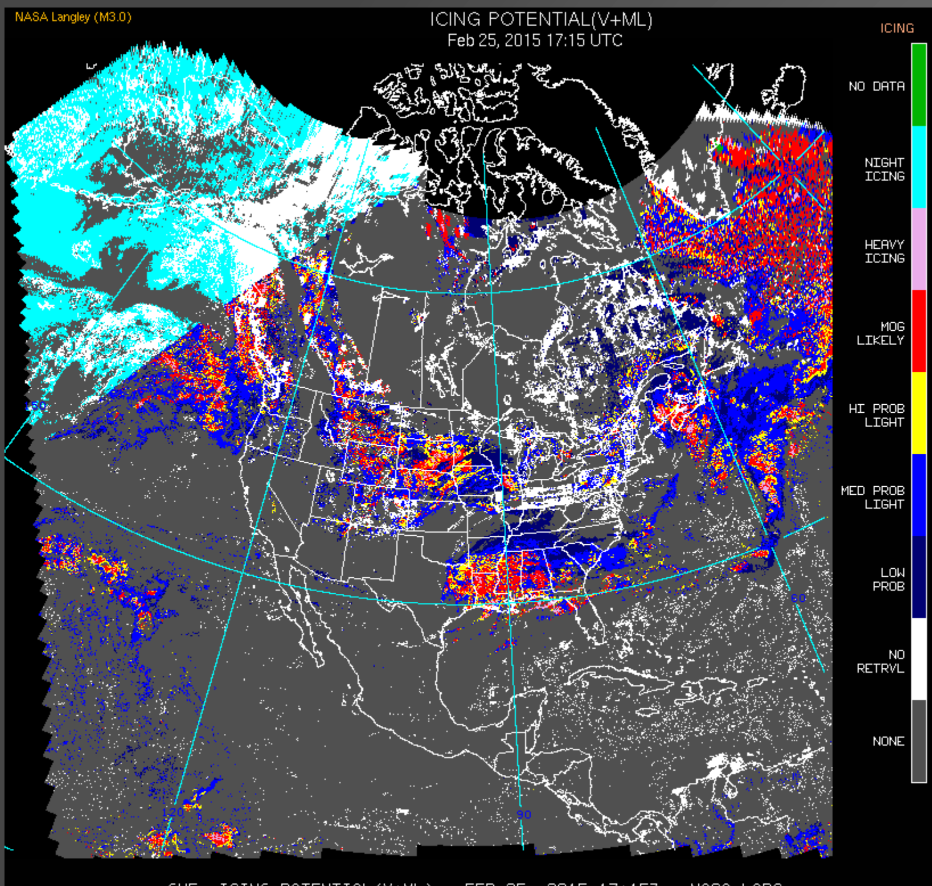
CONUS, 4 km, Half Hourly

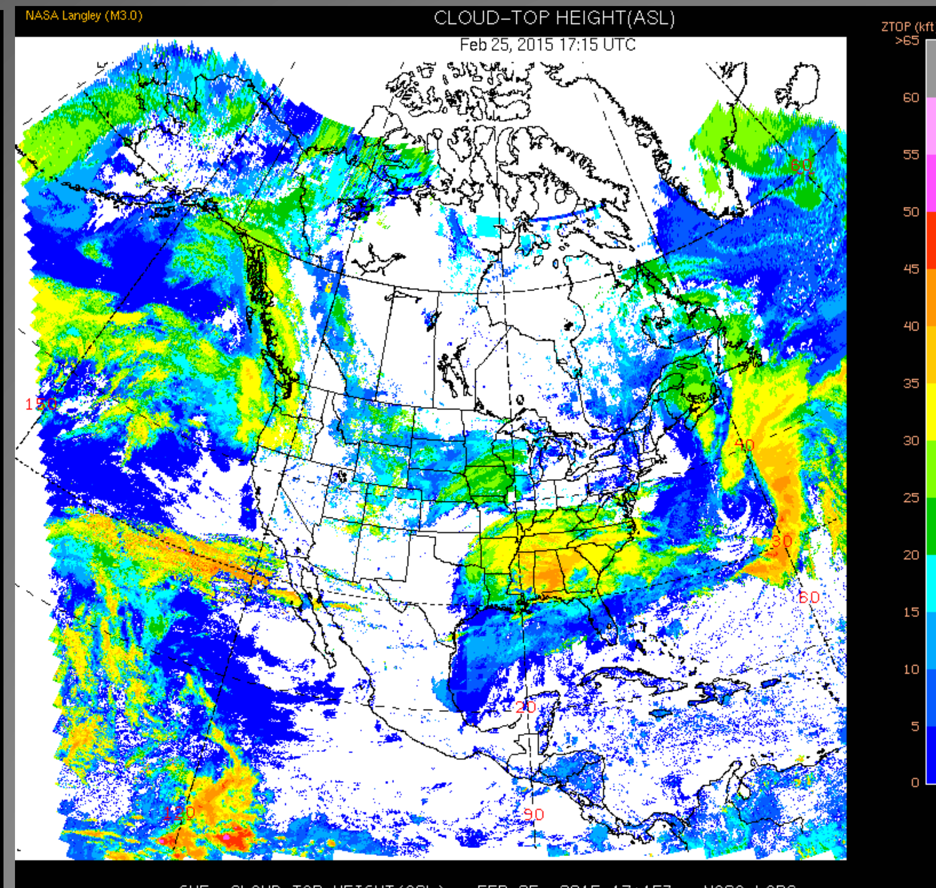


# North American Domain

- Half-hourly analyses from GOES-East and GOES-West

Icing Potential 1715 UTC, 25 Feb 2014 Cloud-top Altitude (kft, AGL)

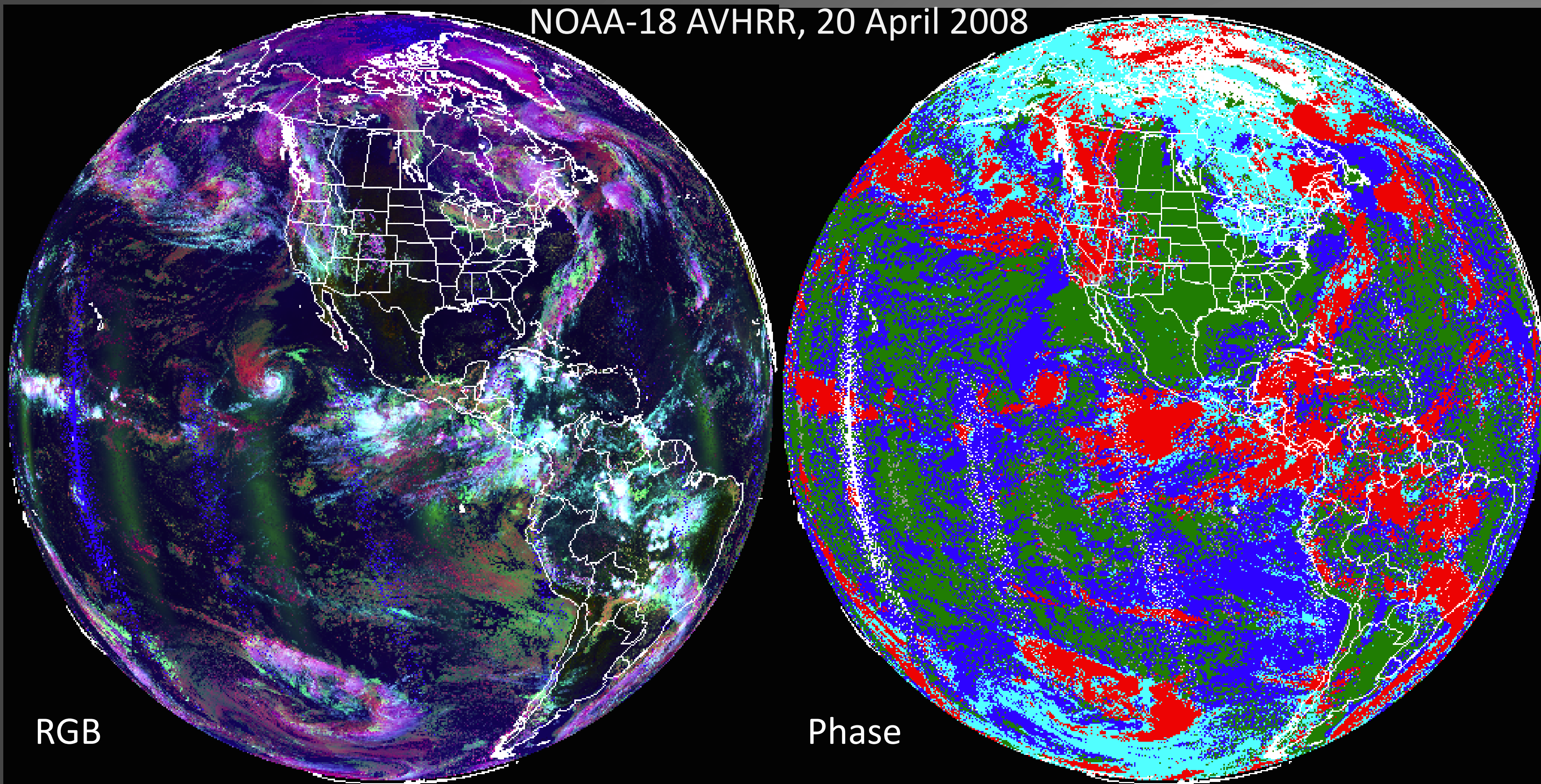



- Data pushed to NCEP
  - assimilated in Rapid Refresh (RAP) NWP model
  - Available to anyone with access to NCEP input products

# Polar-Orbiting Satellites: Global and Polar

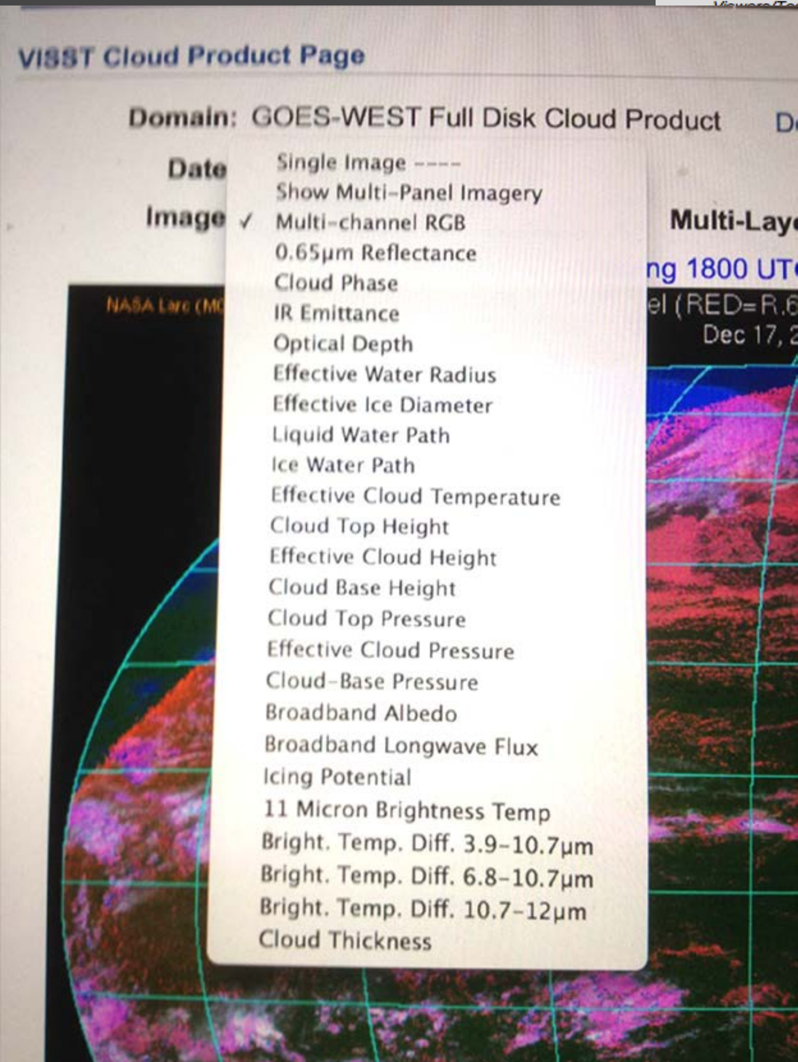
Cloud properties also determined from AVHRR, MODIS, and VIIRS
2-h lag over some polar regions, longer lags elsewhere

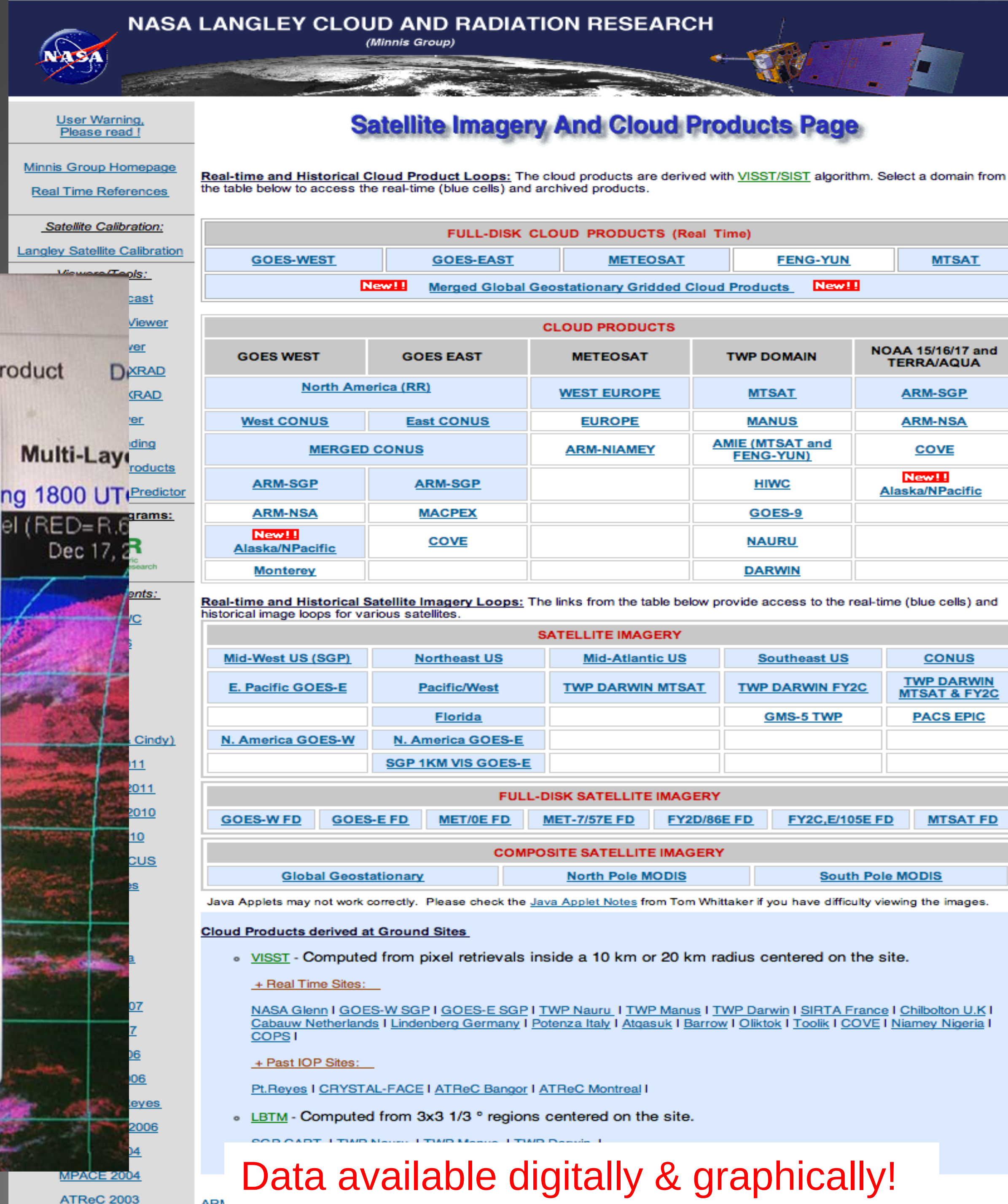



White: clear snow; Cyan: SLW cloud; Blue: warm liquid; Red: ice cloud; Green: clear

Data Can Be Accessed At

cloudsgate2.larc.nasa.gov



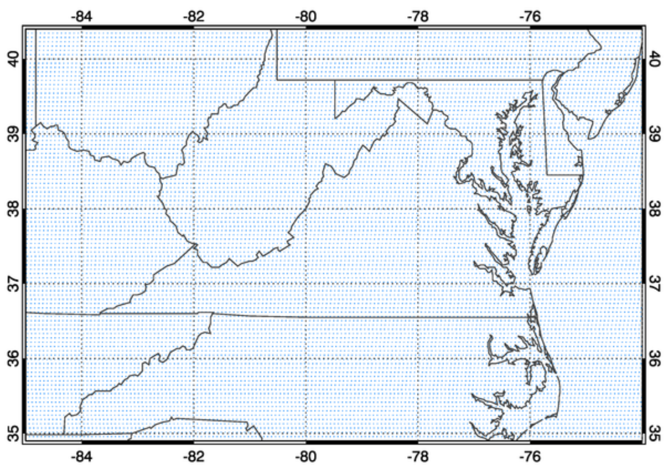



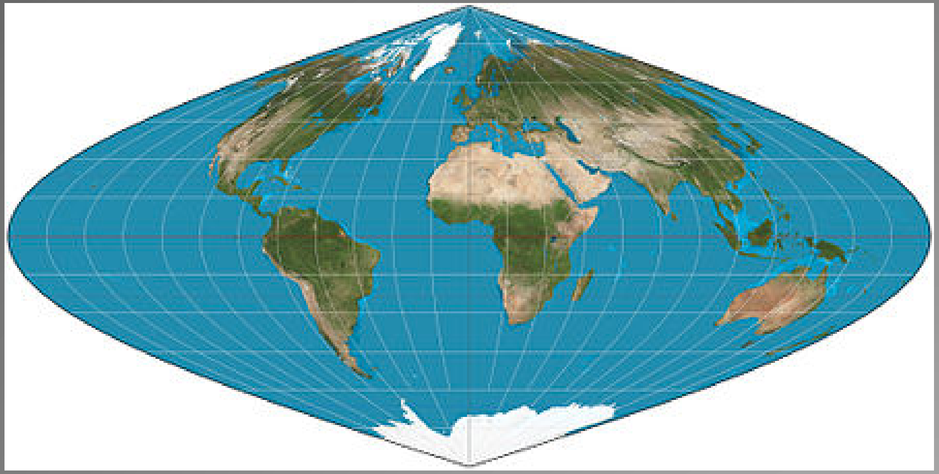

Data available digitally & graphically!

# Future

• Blend GEO & polar-orbiting satellite data to hourly global equal-area grid

- add: INSAT; Himiwari-8 & GOES-R (better time, space, & spectral res)
  MODIS & VIIRS in polar areas
- retain: hi-res regional grids



• We hope to continue improving algorithms & work with users to optimize products (funding always an issue, not a NASA priority)

- display improvements, especially 3-D
- nowcasting => *icing, overshooting tops*
  - *HIWC diagnoses from satellite (uses Darwin & other campaign data)*
- NWP & Icing model assimilation: work on all time and space scales
  - *global, continental, and regional*

# Satellite Products for Icing Analyses and Forecasts

William L. Smith Jr., Patrick Minnis

*NASA Langley Research Center*

*Hampton, VA. USA*

Doug Spangenberg, Cecilia Fleeger,

Rabindra Palikonda

*SSAI, Inc.*

*Hampton, VA. USA*

In-Flight Icing Users Technical Interchange Meeting (TIM)

Washington D.C.

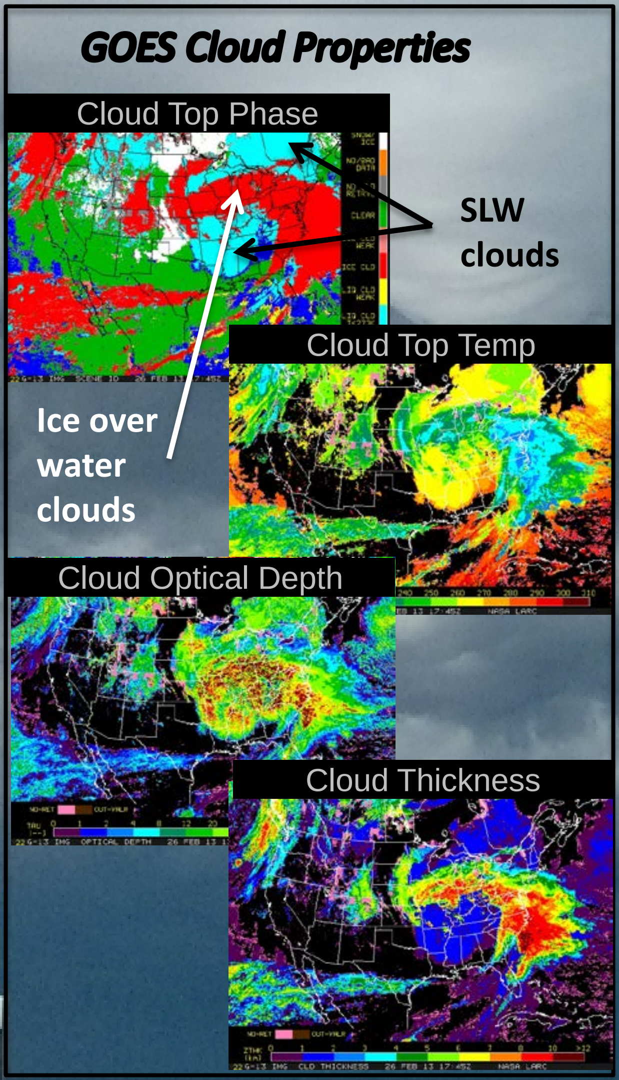
25-26 February, 2015

# Background

- Nowcasting & forecasting clouds and their impacts (e.g. icing) require accurate observations
- A major barrier to accurately predicting clouds & their impacts with numerical models is poor initialization (few/no cloud obs assimilated)
- Satellites observe clouds with high spatial and temporal resolution with sensitivity (higher during daylight) to conditions in which icing occurs
- Satellite cloud retrievals can improve icing diagnoses and forecasts in the following ways:
    1. Used directly to diagnose icing potential
    2. As input into other nowcasting systems, e.g. CIP
    3. As input into weather forecast models and other icing forecasting systems (improved cloud initialization)

# Aircraft Icing


## Satellites observe icing conditions




Cloud property retrievals provide quantitative information on the location for SLW in the atmosphere and on the droplet size distribution (icing potential)

- SLW in cloud tops observed directly (lower level clouds)
  - Cloud Top Phase, Temperature = SLW
  - Effective radius: $R_e = f(N(r))$
  - Liquid Water Path: LWP = f(LWC)
- Ice over water clouds, need to infer embedded icing
  - Exploit multilayer techniques (SLW stratus below Cirrus)
  - For deep ice over water clouds, vertical structure important. Satellite retrievals can be used to constrain the problem during the daytime but other information also needed

# NASA LaRC Satellite Icing Algorithms

## GOALS

- **Provide solutions** for the full range of cloud conditions where icing is found
    1. Low cloud algorithm (Low, liquid topped clouds)
    2. Multi-layer algorithm (cirrus over stratus)
    3. Thick ice over water cloud algorithm (i.e. winter storms and convection)
- **Primary Inputs:** Satellite cloud retrievals (available globally, over data sparse areas, and with high spatial and temporal resolution)
- **Product outputs**: icing probability, potential intensity, expected altitude range
- **Future work:** blend in other realtime information when/where available (e.g. radar, ceilometer, thermodynamic profiles over CONUS)

# NASA LaRC Satellite Icing Algorithms

1. **Low Cloud Algorithm**
   - Cloud top phase and temperature (Tcld) identify SLW
   - Satellite LWP and $R_e$ correlated with icing PIREPS to develop relationships
   - Larger values of LWP, $R_e$ correspond with higher probability and more intense icing
   - Algorithm tuned to maximize both POD (light) and POD (MOG)
   - Recently added heavy icing category based on large Re

2. **Multilayer algorithm (cirrus over stratus)**
   - Derive lower level Tcld, LWP (F.-L. Chang technique) and apply low cloud icing algorithm
   - Recently updated and not yet validated

# NASA LaRC Satellite Icing Algorithms

## 3. Thick ice over water cloud algorithm

*Employs a cloud water content profiling technique (fully constrained with satellite cloud retrievals) to estimate the embedded supercooled LWC(z) which is then used to infer the icing potential*

To develop and test, we use cloud properties and information from:

- NASA ATRAIN data: MODIS (satellite imager) flying in formation with the CloudSat cloud radar and the CALIPSO cloud lidar
- DOE ARM data: Cloud retrievals from ground-based cloud radar, lidar and microwave radiometer data co-located with GOES satellite cloud retrievals
- NOAA RUC/RAP cloud analyses
- Icing PIREPS for validation

# NASA LaRC Satellite Icing Algorithms

## 3. Thick ice over water cloud algorithm (Primary Elements)

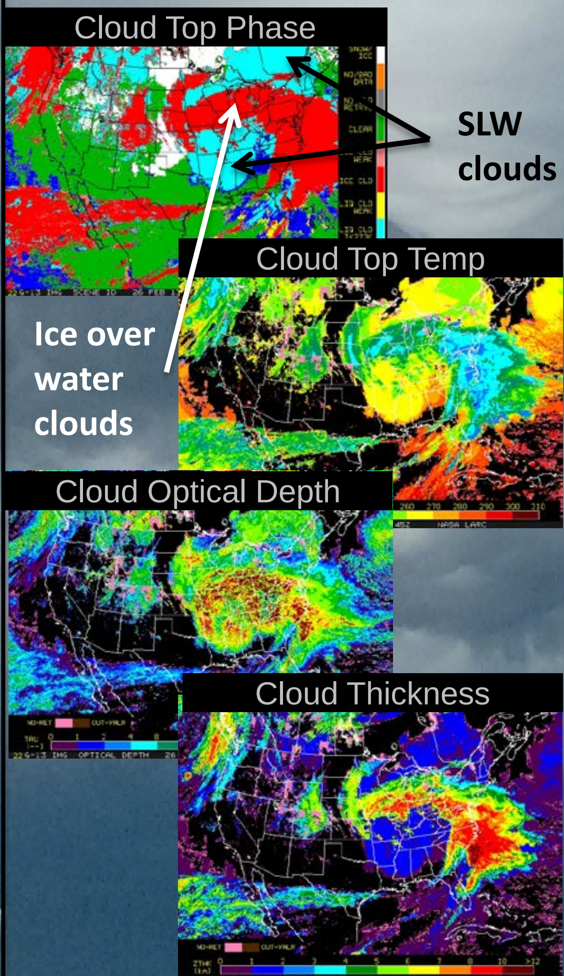
Satellite Cloud Retrievals ($T_{top}$, TWP, $Z_{top}$, $Z_{base}$) define cloud type and constrain icing estimates. Cloud vertical structure is assessed *apriori* and climatologically as function of 50+ cloud types (using ARM, ATRAIN, RUC/RAP data) and stored in lookup tables. These include:

- Probabilities for cloud in the vertical profile, Pcld(z)
- Probabilities for SLW, Pslw(z); *Picing* = Pcld*Pslw
- Guidance on the vertical distribution of total cloud water, TWC(z)
- Guidance for partitioning liquid from ice: TWC(z)=IWC(z)+LWC(z)
- Guidance to map LWC to icing intensity: Politovitch (2003) air foil study
- *Picing* thresholds developed from correlations with PIREPS for estimating icing altitude boundaries (function of cloud type)

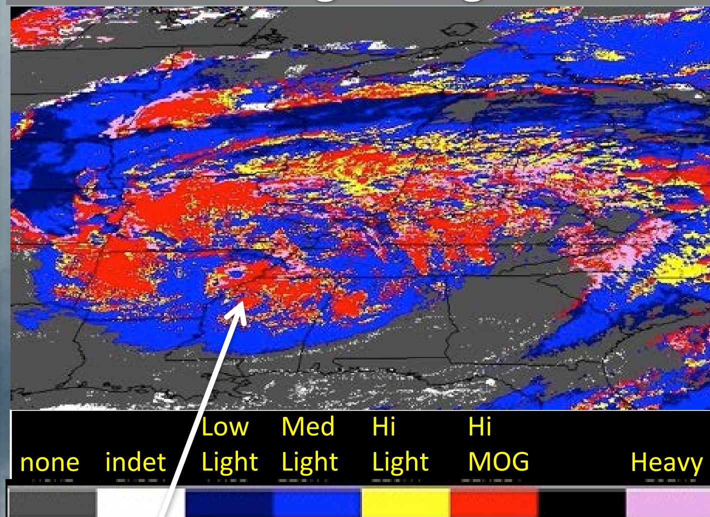
# Aircraft Icing

## Example of current satellite icing product

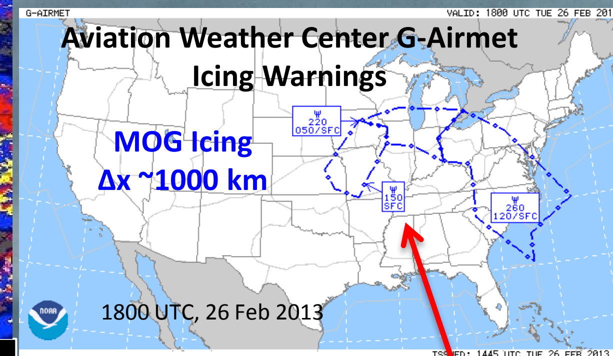
### GOES Cloud Properties

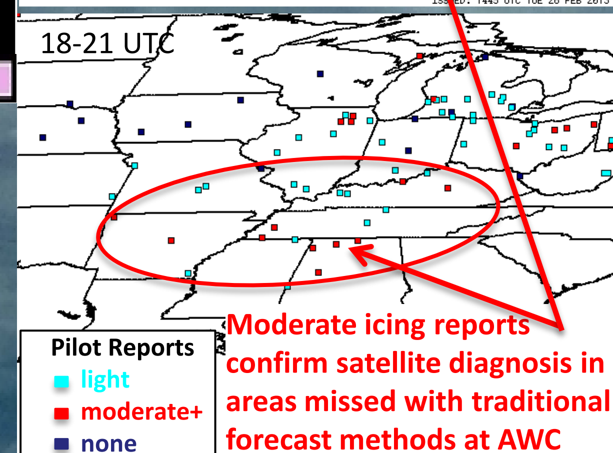



### Satellite Flight Icing Threat



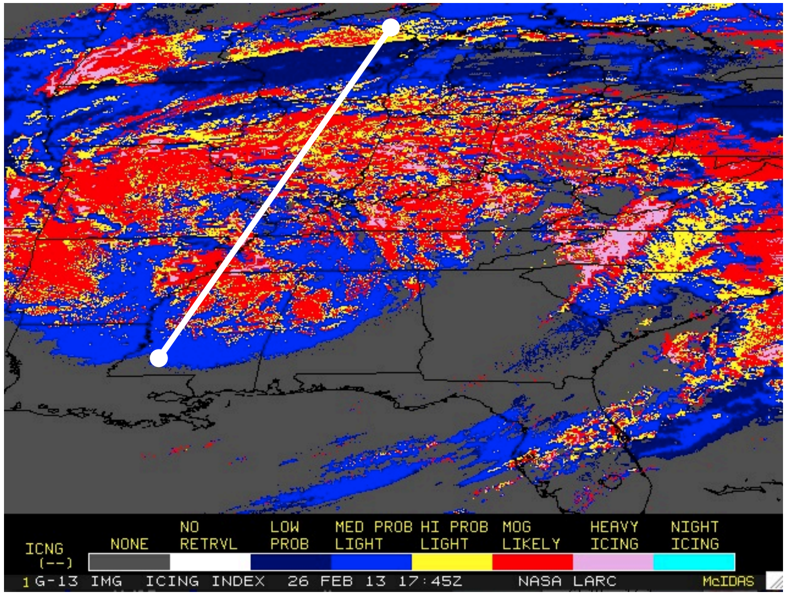

***Satellite method provides early warning and improved resolution of the icing threat not captured in current forecasting techniques and reduces overwarning.***

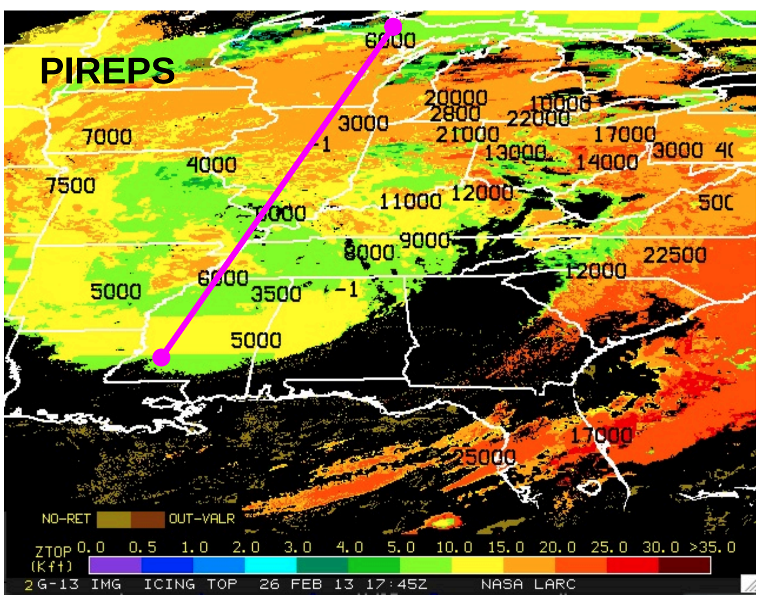




Moderate icing reports confirm satellite diagnosis in areas missed with traditional forecast methods at AWC

## GOES Icing Potential

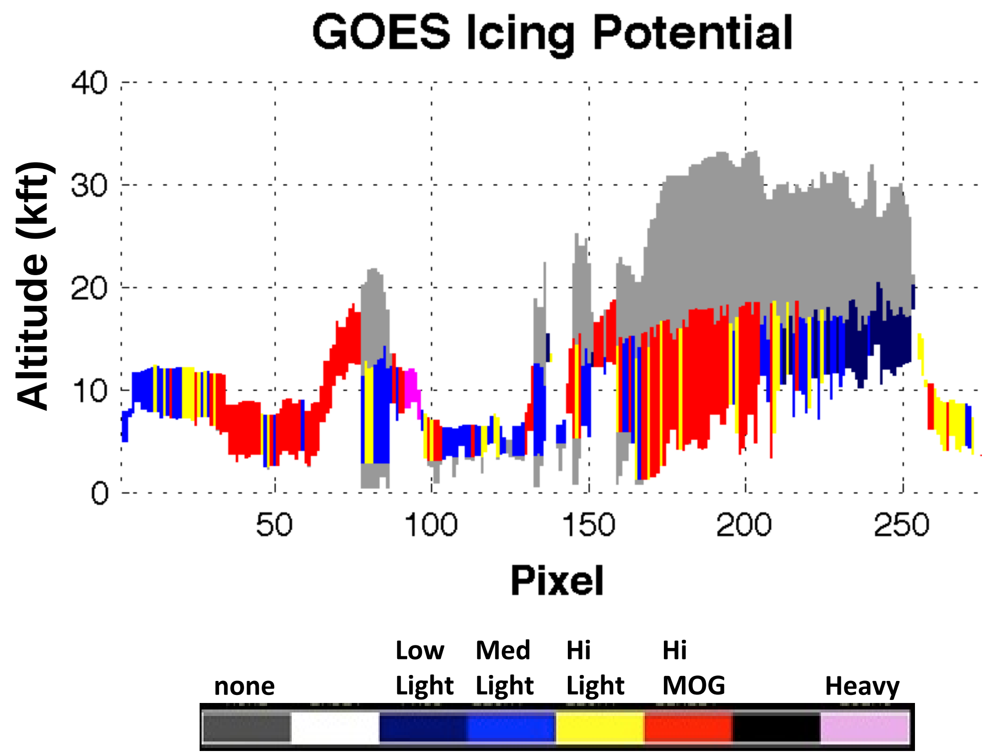



## GOES Icing Layer Top Altitude




# 3-D Icing Potential

Feb 26, 2013 (1745 UTC)

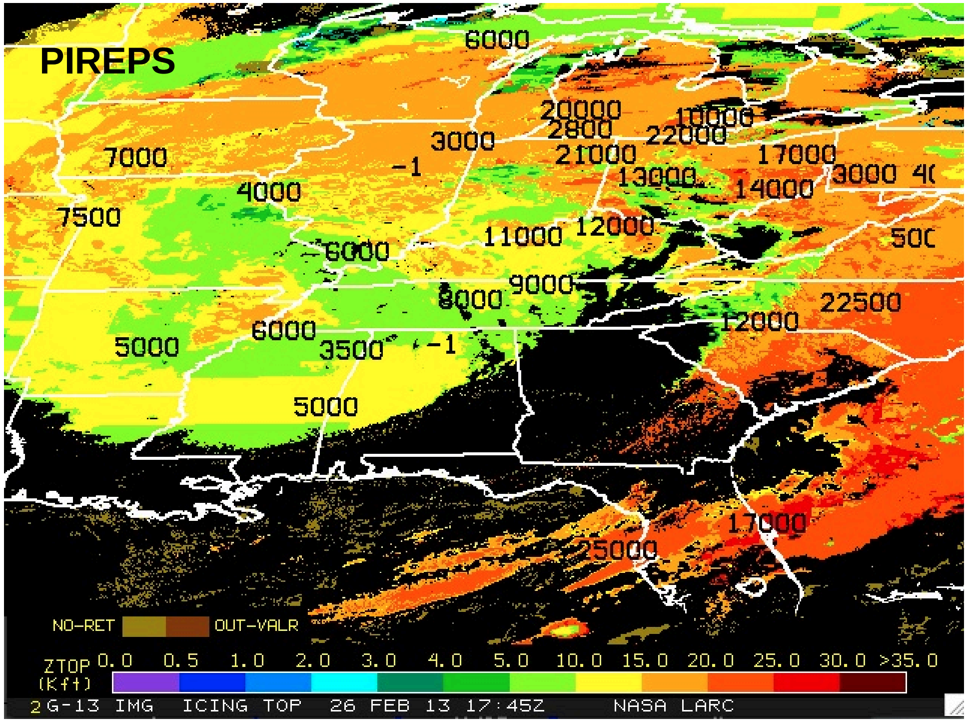



Single-layer algorithm

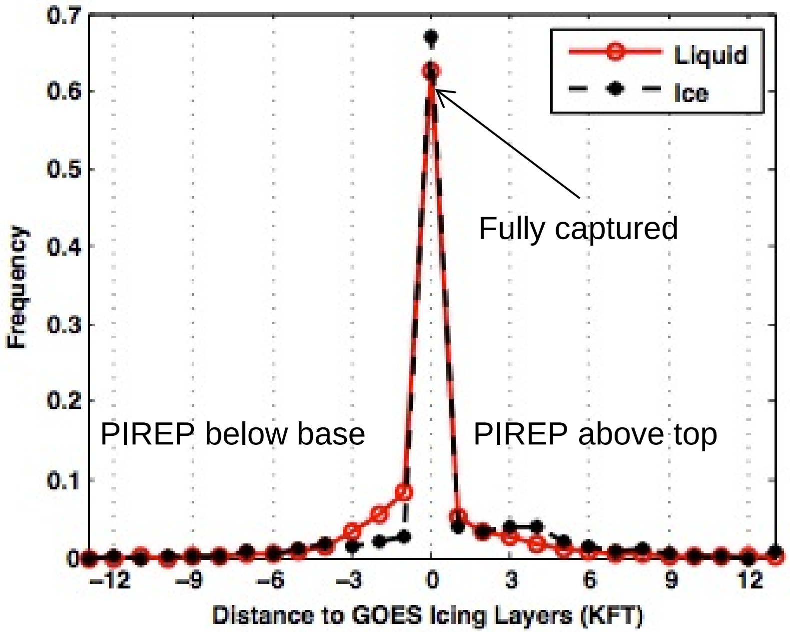
# Verification with PIREPS
# Icing Layer Altitude

***Icing layer top altitude:*** *PSLW thresholds (cloud type dep.) tuned with PIREPS*
***Icing layer base altitude:*** *Cloud base or freezing level*

GOES Icing Layer Top Altitude




Frequency of icing PIREPS relative to satellite icing layer altitude boundaries




***Derived icing altitude boundaries capture most icing PIREPS found in ice and liquid topped clouds***

# Icing Potential Verification

Jan – Mar, 2013 (USA)

Satellite icing assessed in 20-km radius region at PIREP

## Icing Detection

| Satellite Method | N | PODY | Hit Rate |
|---|---|---|---|
| OVC Liquid Clouds | 5759 | 99% | 90% |
| OVC Ice Clouds | 2713 | 98% | 83% |
| All OVC Regions | 11851 | 99% | 88% |

**Icing detection beneath ice clouds is almost as accurate as that for unobscured low-level liquid clouds**

## Icing Intensity also has skill

| Source | N | PODL | PODM | Accuracy | Pirep %MOG | Sat |
|---|---|---|---|---|---|---|
| Liquid Clouds | 5013 | 76% | 66% | 73% | 27 | 36 |
| Ice Clouds | 2236 | 80% | 47% | 72% | 26 | 27 |

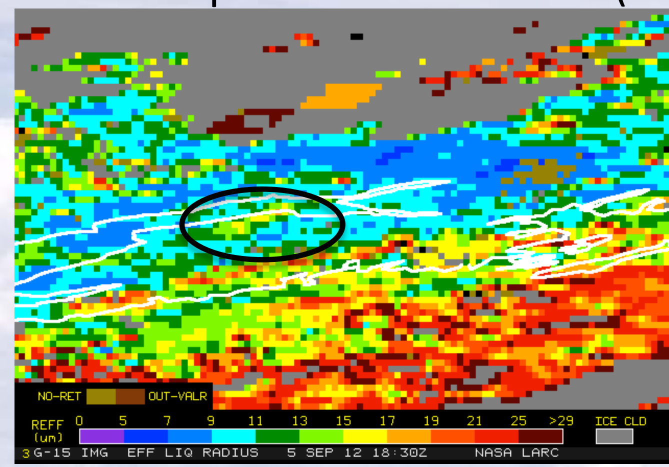
**Intensity accuracy similar for liquid and ice clouds. Too much MOG for low clouds(?)**

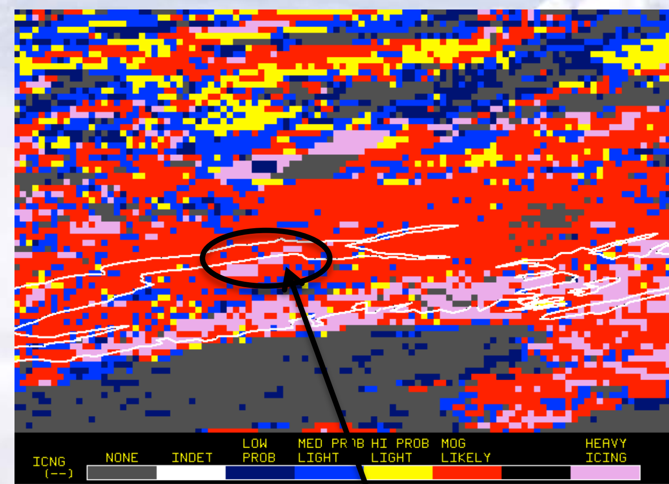
# Case studies used to evaluate heavy icing index

## 9/5/2012 Era Flight 847
## Anchorage To Homer
## 5000 feet altitude loss due to icing


- Flight reportedly reached 12K ft and then lost 5000 feet altitude and returned to Anchorage
- 15 on board, including 12 passengers, a pilot, co-pilot, and flight attendant


Water Droplet Effective Radius (um)




**Heavy icing detected from GOES in vicinity of aircraft incident**

Icing condition not well forecasted by Alaska NWS

# Heavy Icing Case Studies

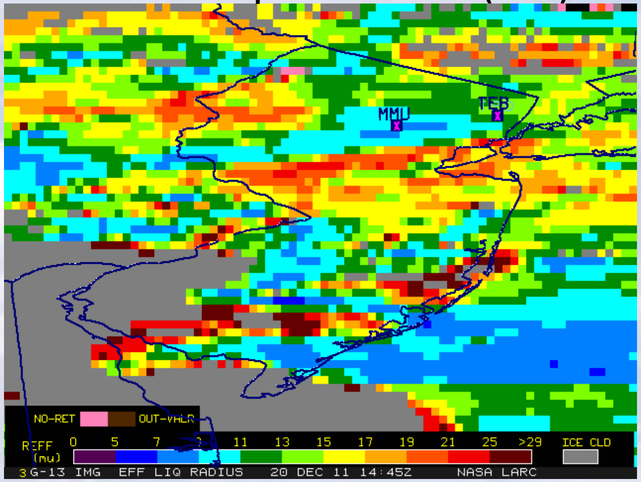
Socata TBM-700 crash near Morristown, NJ

Dec 20, 2011 (10am)

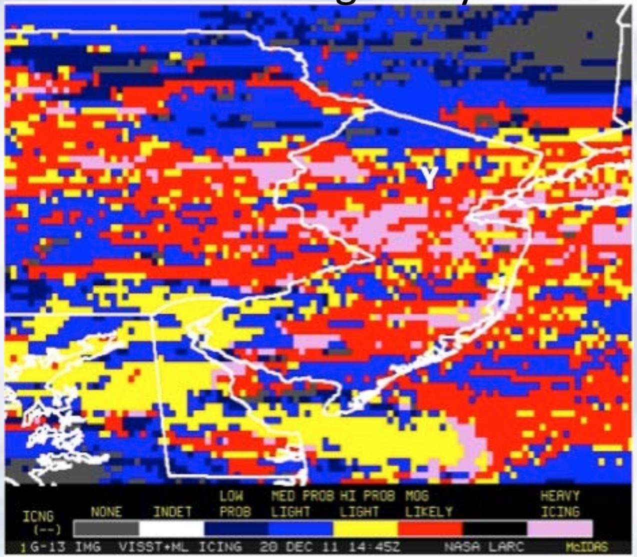
- All 5 on board were killed
- AWC icing AIRMET had been issued for area and a general icing advisory issued to Pilot by ATC
- Numerous severe icing reports from jetliners filed near the time of the crash
- Severe icing advisory not issued until 11am
- Satellite analysis indicates lots of potentially heavy icing in the area. Thin higher layer obscured heavy icing near crash site

**PIREPS are currently the primary trigger for SVR icing advisories**

Water Droplet Radius (um)



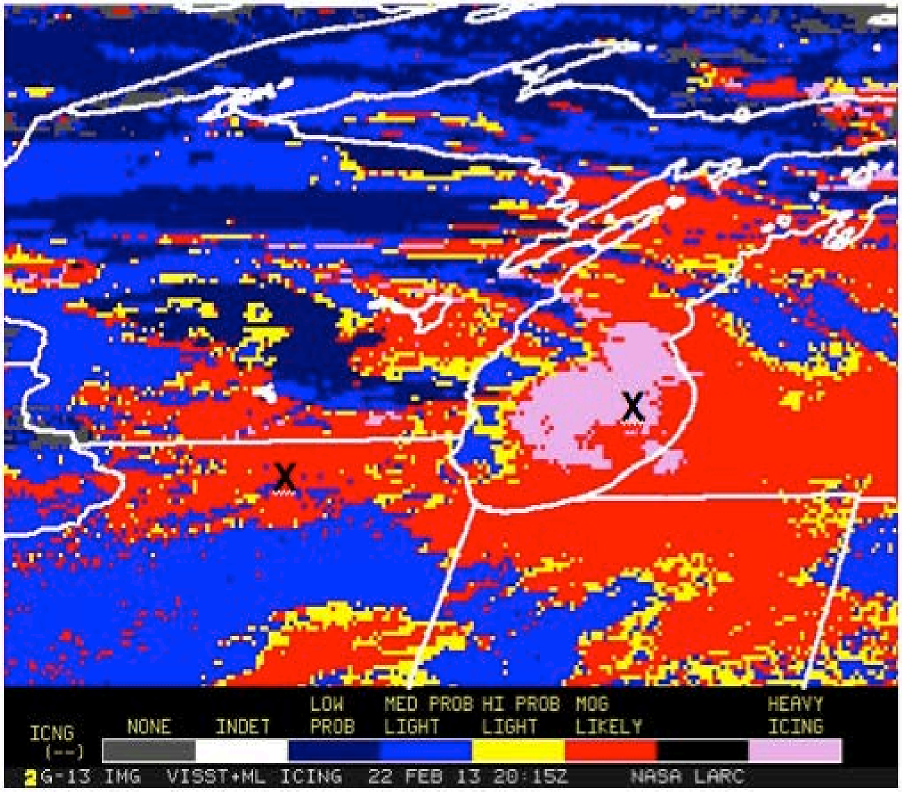

Satellite Icing Analysis



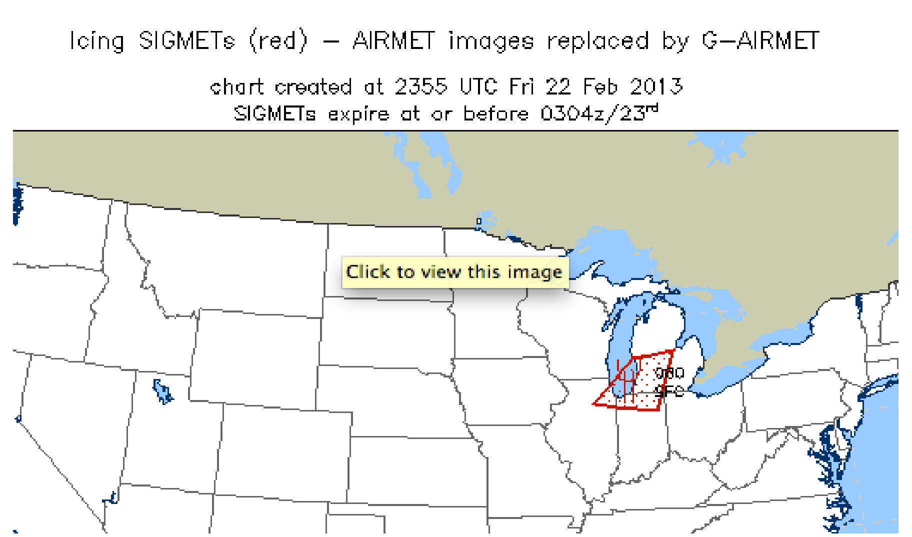
# Aircraft Icing


## Satellite method provides early warning for heavy icing

22 Feb 2013 (2015 UTC)




X – denotes severe icing PIREPs




**Icing SIGMET not issued until 2355 z**

# Comments on Profiling Technique

- Provides information on cloud vertical structure that are fully constrained with NRT satellite retrievals at the resolution of the satellite imager
    - Includes profiles of the probabilities for cloud and SLW, LWC and IWC profiles.
    - Demonstrated for Cirrus (no icing threat) and deep SL ice over water clouds
    - First estimates of IWP and LWP in mixed phase clouds from operational satellite, and unprecedented accuracies compared to other satellite techniques
    - IWC/IWP estimates agree well with active sensor retrievals and in situ measurements over a wide range of cloud conditions
    - Embedded LWP estimates agree well with microwave radiometer data and are also confirmed by pilot reports of icing conditions (**PIREPS are a valuable resource!**)
    - Results indicate that weather forecast models (i.e. RUC/RAP) already produce realistic clouds in many respects but not at the right place and time – not surprising considering lack of cloud obs assimilated
- When applied to GEO data, the profiling technique can provide a 4D cloud hydrometeor analysis for up to two cloud layers which should be useful for other applications and assimilation into forecast models. Some assimilation work is underway for convection but not icing.

# Summary

• Satellite cloud retrievals improve spatial and temporal resolution of clouds and icing conditions compared to traditional nowcasting/forecasting methods

• Further improvements possible with other channels on newer imagers (e.g. 1.6 and 2.2 µm on GOES-R penetrate deeper into cloud and help over snow )

• CONUS icing products will be delivered to NWS aviation WFO's for evaluation and feedback late 2015/2016 (via GOES-R Proving Ground). All LaRC NRT products, including other domains, are available now from NASA and some at NCEP

• Potential path to operations exists and is being pursued to improve icing diagnoses. Forecasting and other domains besides GOES-R is another matter (not funded)

• Satellite retrievals are not perfect. Much more work is needed to better understand uncertainties, incorporate new channels, refine the methods, package these information most appropriately for users, and acquire feedback

# NASA LaRC USA Icing Page

http://cloudsgate2.larc.nasa.gov        Aircraft Icing link on left

# Recent Satellite Icing References

Smith, W. L., Jr., P. Minnis, C. Fleeger, D. Spangenberg, R. Palikonda, L. Nguyen, 2012: Determining the Flight Icing Threat to Aircraft with Single-Layer Cloud Parameters Derived from Operational Satellite Data. *J. Appl. Meteor. Climatol.*, **51**, 1794–1810.

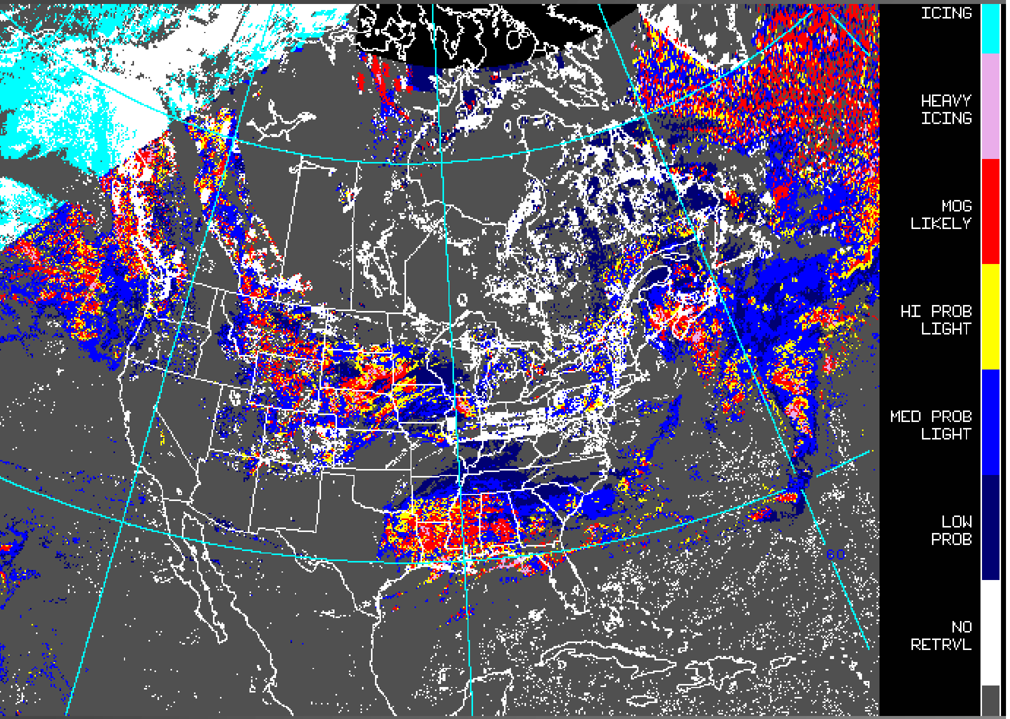
Smith, W. L., Jr., 2014: 4-D cloud properties from passive satellite and applications to resolve the flight icing threat to aircraft. PhD. Dissertation, University of Wisconsin-Madison, 165 pp.

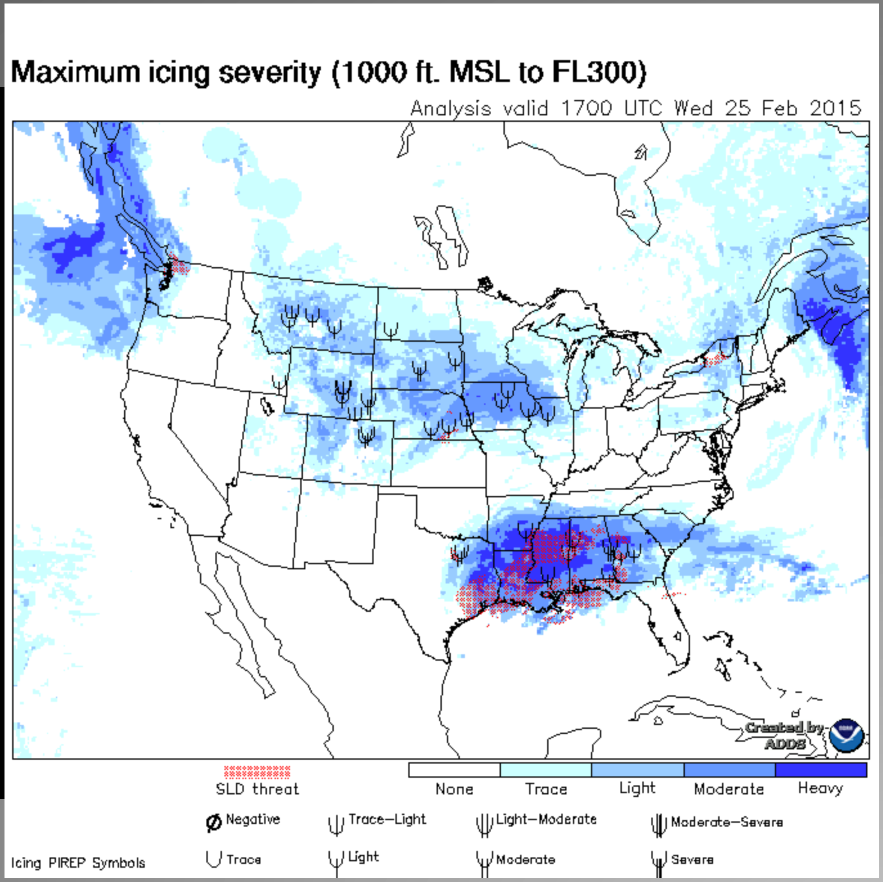
## Extra Slides

# North American Domain

- Half-hourly analyses from GOES-East and GOES-West

Icing Potential 1715 UTC, 25 Feb 2014 Cloud-top Altitude (kft, AGL)



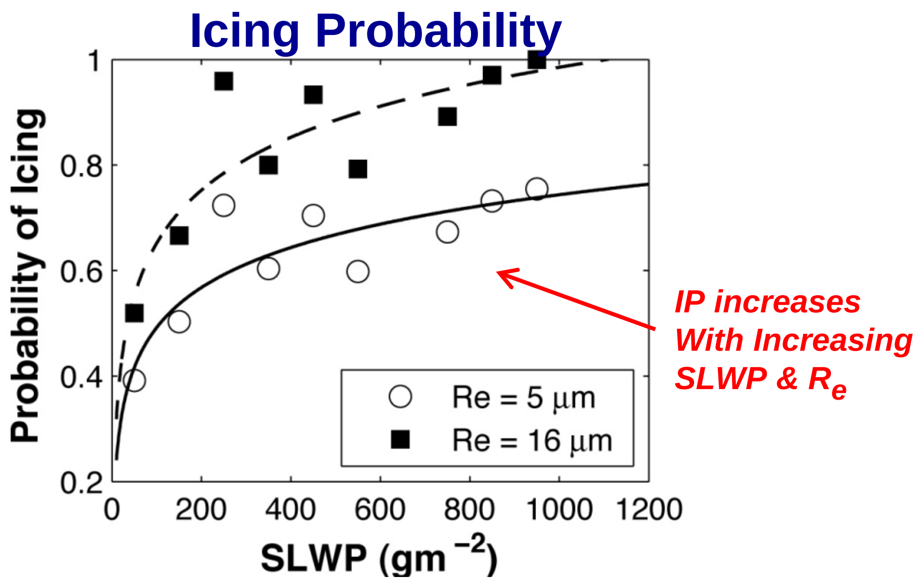




- Data pushed to NCEP
  - assimilated in Rapid Refresh (RAP) NWP model
  - Available to anyone with access to NCEP input products

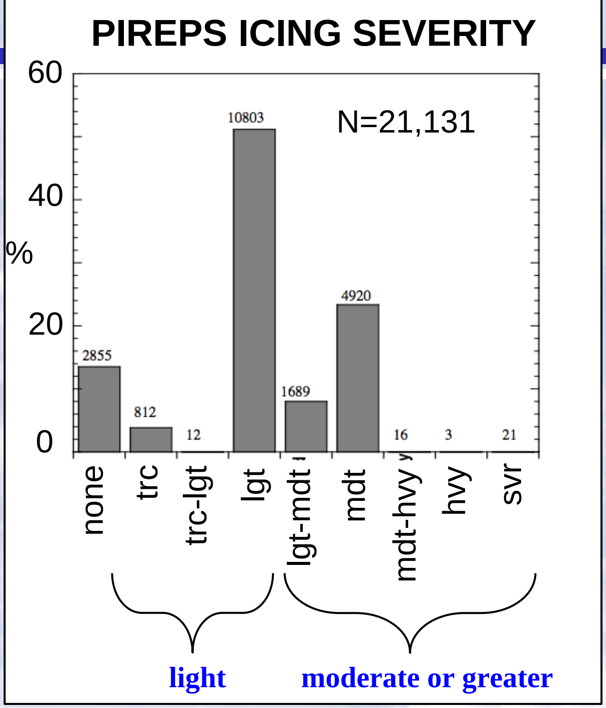
# Satellite Icing Algorithms

## (1) Low cloud algorithm (SLW clouds)

- Cloud top phase, temperature identify SLW directly
- Match satellite retrievals of SLWP and $R_e$ with PIREPS to develop relationships to icing threat
- LWP scaled to layer above freezing level (SLWP)




Smith et al. 2012 (JAMC)




## Icing Intensity

SLWP Thresholds developed to separate light from MOG intensities

| SURFACE | SLWP ($g/m^2$) |
|---|---|
| All | 405 |
| Snow | 475 |
| No Snow | 379 |

# Thick Ice Over Water Cloud Algorithm

Primary elements:

- TWP parameterization (guidance from ground-based sensors)
  - Satellite retrieved IWP ≠ TWP or IWP for these clouds
  - IWP retrieval assumptions are violated: (not all ice, Re(z) ≠ const)

- Climatological cloud type dependent functions (stored as lookup tables) that describe cloud vertical structure:
  1. the probability for cloud in vertical profile relative to the satellite-derived cloud boundaries (guidance from CloudSat+CALIPSO)
  2. typical vertical distributions of total cloud mass ( i.e. derive TWC(z) from TWP) (from CloudSat+CALIPSO and RUC/RAP cloud analyses)
  3. The probability for liquid in the vertical profile (from RUC/RAP)
  4. Guidance on liquid and ice partitioning to estimate IWC(z) and LWC(z) from TWC (z) (from RUC/RAP)
  5. Method to map LWC(z) to icing intensity at levels with T<0°C (air foil modeling study, Politovitch (2003)
  6. Consolidate for users: output max icing probability and intensity for the layer along with icing layer altitude boundaries

# Vertical Structure: Cloud Probability

**Cloud probability vertical distribution functions, Pcld(z), relative to imager cloud boundaries and as a function of cloud type.**

**CloudSat/CALIPSO ground-truth**

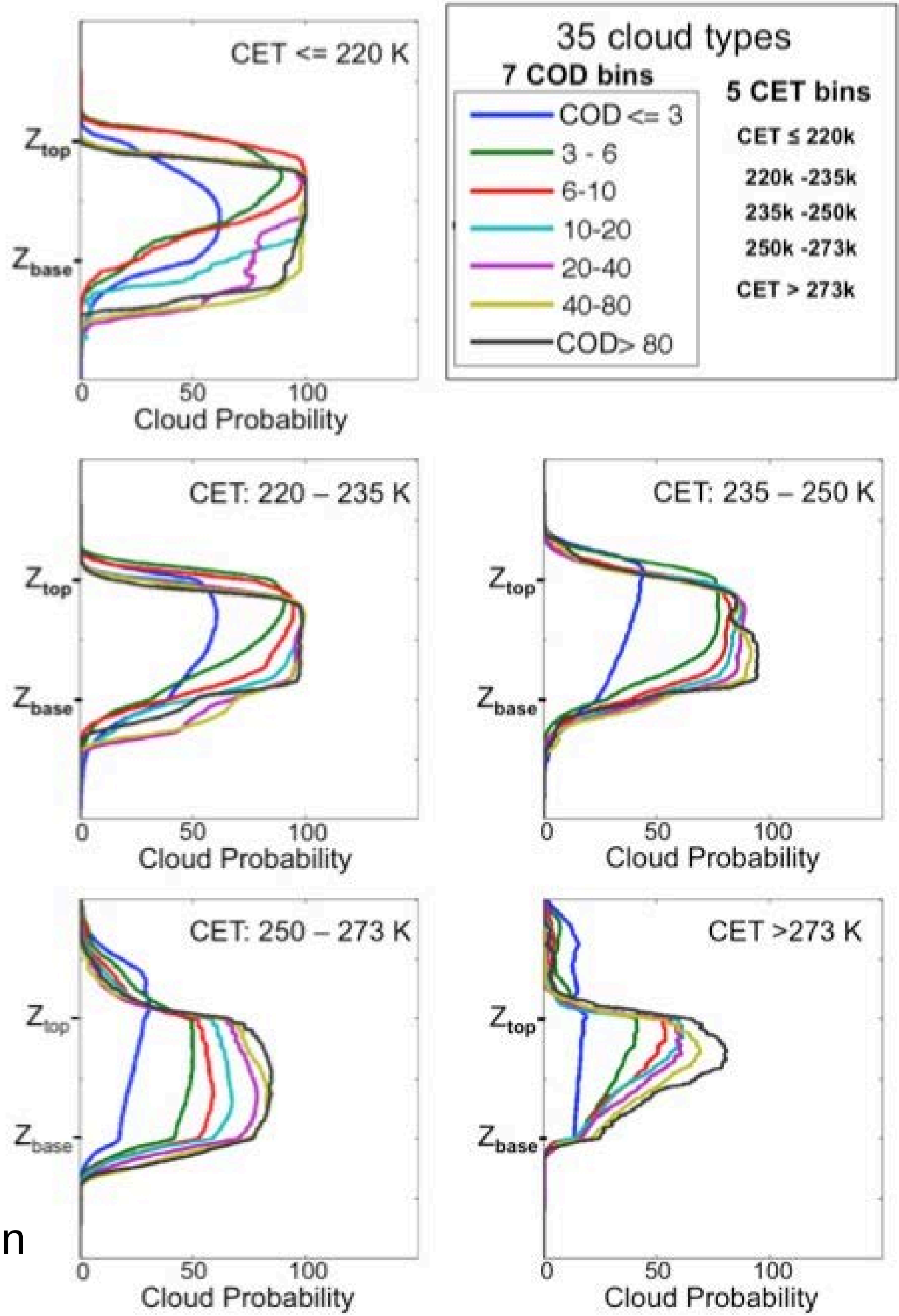
**SL only, ML could reduce errors**

**Retrieved cloud boundaries pretty good but errors are a function of cloud type**

**Cloud probabilities higher for optically thick clouds (vs thin)**

**Cloud probabilities higher for cold (high) clouds than mid level (overlap problem) and low clouds (geometrically thin so errors magnified)**

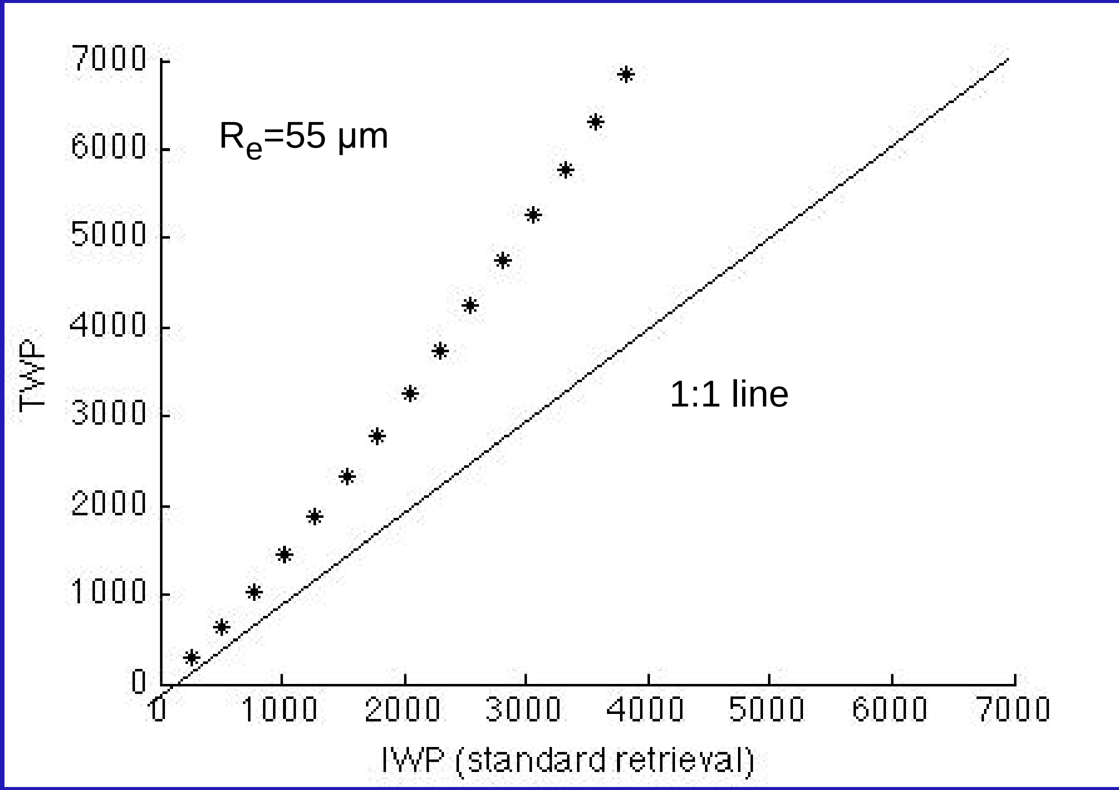
Could be used to improve CTH assimilation in model analyses (cloud building logic)



# Thick Ice Over Water Cloud Algorithm

TWP parameterization:

- Based on correlations between GOES cloud retrievals (COD, $R_e$) and ARM Microbase product (Radar/MWR retrievals) at SGP



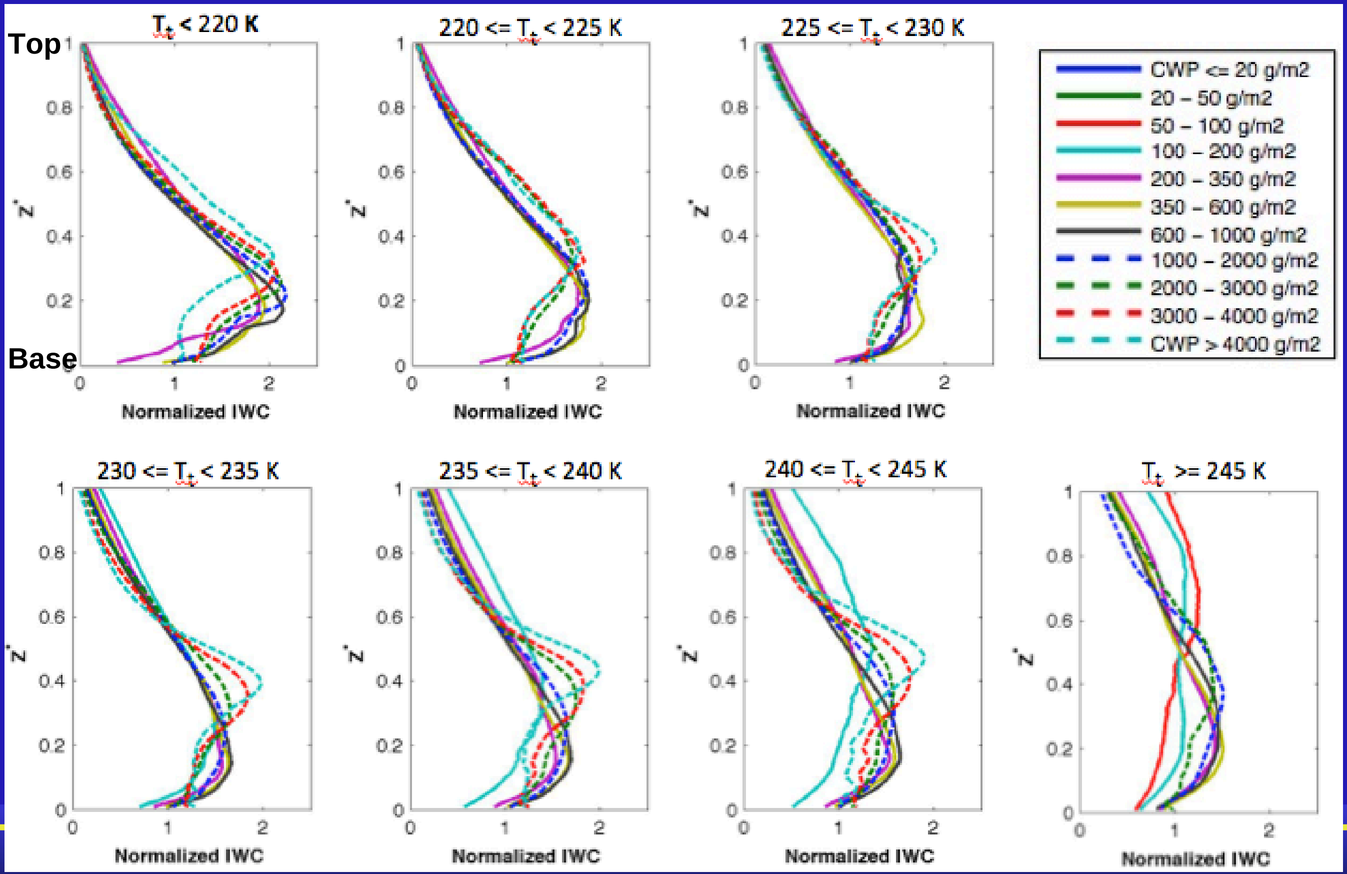

TWP nearly twice as large as the standard satellite retrieval of IWP for optically thick ice over water clouds

# Thick Ice Over Water Cloud Algorithm

## Normalized TWC Profiles, Hybrid (RUC + CloudSat/CALIPSO)

50+ cloud types defined by TWP, $T_t$ ; Ice-topped clouds with COT > 10

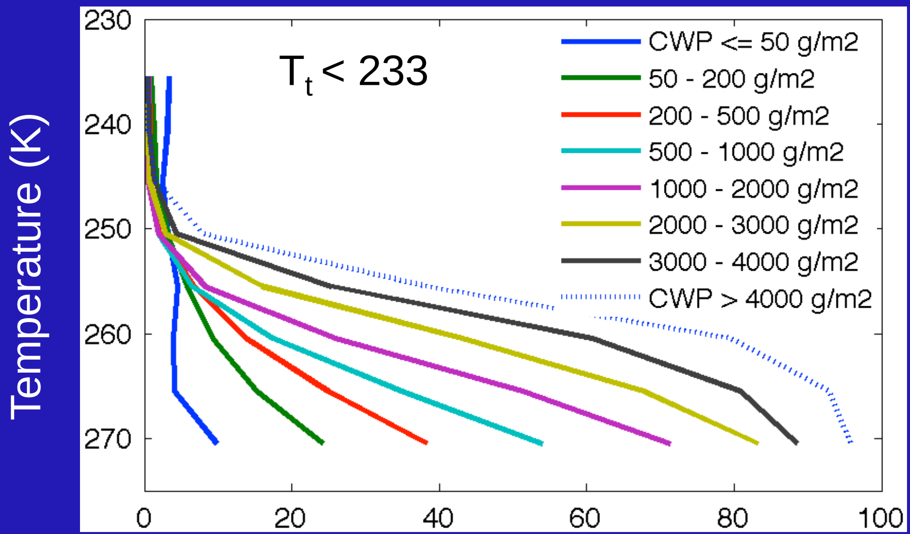
*Used to estimate TWC(z) from TWP (pixel level)*



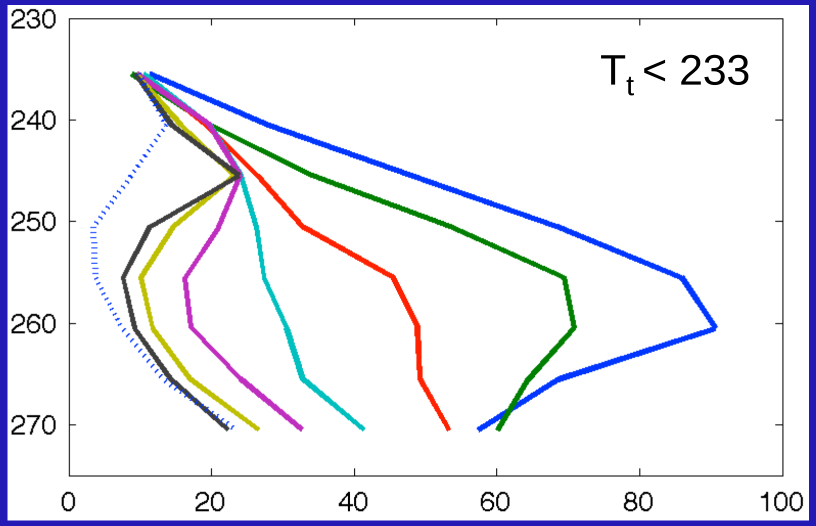
# Thick Ice Over Water Cloud Algorithm

## SLW Probability and Speciation (Thompson microphysics)

Climatological, function of T for lots of cloud types




SLW Probability (%)




SLW liquid/ice mass Fraction (%)

Used to define icing layer boundaries and derive IWC(z), LWC(z) from TWC(z)

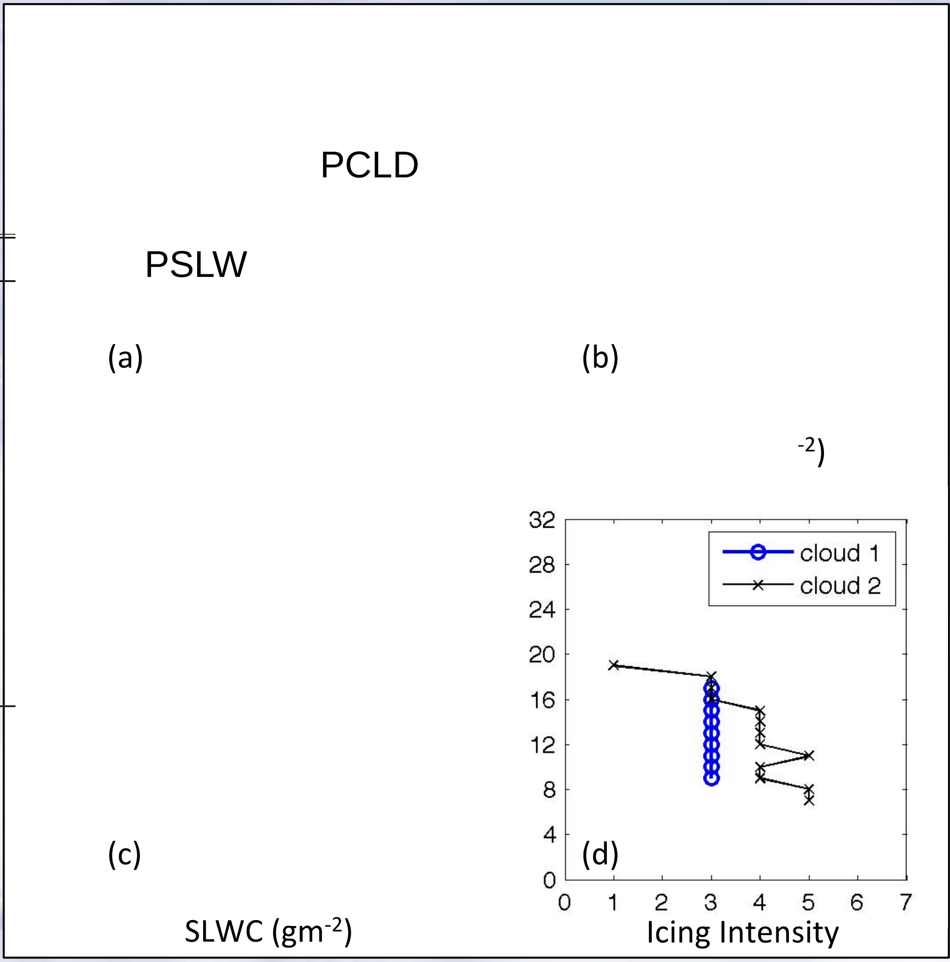
# NASA LaRC Satellite Icing Algorithms

## Example icing retrieval for two ice over water clouds

Cloud 1: COD=50

Cloud 2: COD=100

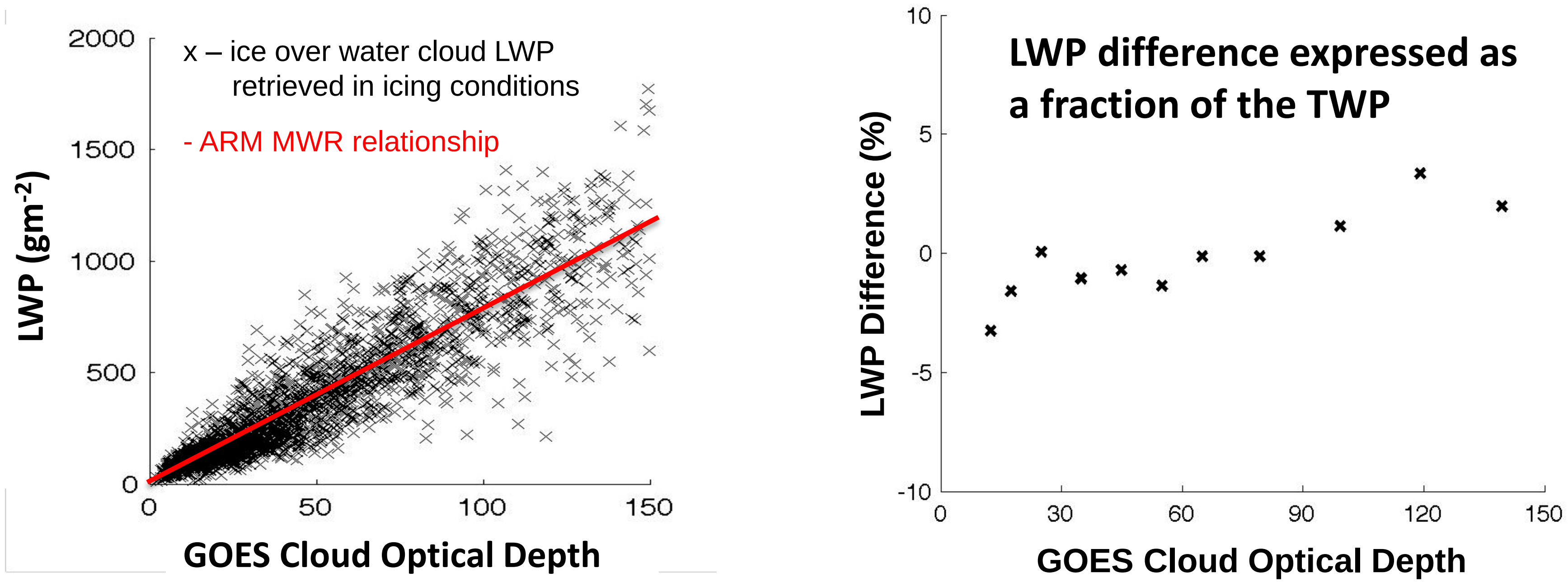
| Parameter | Source | Cloud 1 | Cloud 2 |
|---|---|---|---|
| COD | VISST | 50 | 100 |
| CER (µm) | VISST | 50 | 50 |
| IWP ($gm^{-2}$) | VISST | 1500 | 3000 |
| TWP ($gm^{-2}$) | parameterization | 2212 | 5004 |
| LWP ($gm^{-2}$) | parameterization | 321 | 679 |
| LWP ($gm^{-2}$) | Profile method | 200 | 362 |
| CTH (kft) | VISST | 35.4 | 35.4 |
| CBH (kft) | VISST | 8.9 | 5.9 |
| Zfrz (kft) | RAOB | 3.9 | 3.9 |
| ITH (kft) | Profile method | 17.5 | 19.0 |
| IBH (kft) | Profile method | 8.9 | 5.9 |
| Icing Intensity Index (max) | Profile method | 3 | 5 |
| Icing Probability (max) | Profile method | 0.63 | 0.9 |
| FIT Intensity Index | Profile method | Light | MOG |
| FIT Probability Index | Profile method | Medium | High |




Max Picing, intensity in vertical profile used to define icing potential for layer

# LWP Validation

Relationship between COD and the LWP derived from GOES using the profiling technique (with RUC liquid/ice relationships) agrees with the relationship found between GOES and ARM MWR data



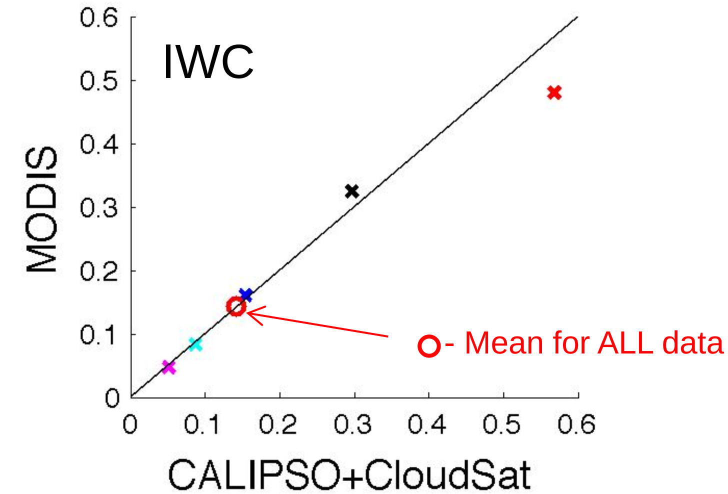

Suggests that the RUC/RAP (Thompson microphysics) cloud phase partitioning is good and that the satellite profiling technique is inferring the right amount of liquid water

# Imager IWC/IWP retrievals using profiling method agree well with CloudSat/CALIPSO

**Monthly averages: April 2010 (CONUS)**

**IWC ($g/m^3$)**

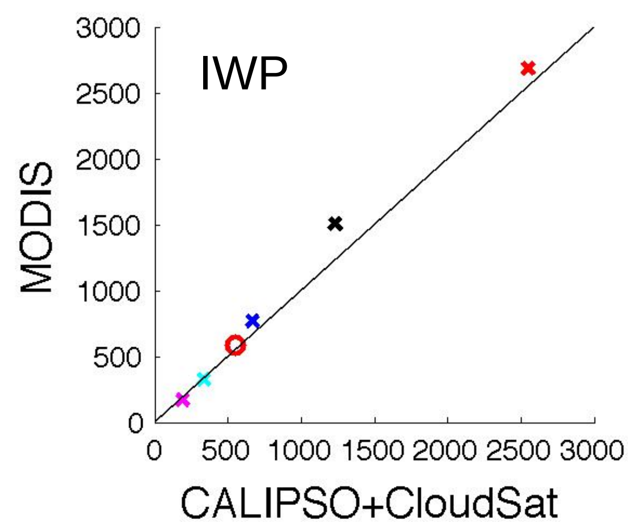
| COD BIN | CALIPSO+ CloudSat | MODIS | BIAS | N |
|---|---|---|---|---|
| 10-20 | 0.051 | 0.047 | -8% | 5083 |
| 20-40 | 0.087 | 0.083 | -5% | 4149 |
| 40-80 | 0.154 | 0.161 | 5% | 2635 |
| 80-150 | 0.297 | 0.325 | 9% | 730 |
| 150 | 0.568 | 0.480 | -15% | 965 |
| ALL | 0.141 | 0.143 | 1% | 13562 |




Assessed at altitudes above -20C level

**IWP ($g/m^2$)**

| COD BIN | CALIPSO+ CloudSat | MODI S | BIAS | N |
|---|---|---|---|---|
| 10-20 | 191 | 169 | -12% | 5083 |
| 20-40 | 333 | 324 | -3% | 4149 |
| 40-80 | 668 | 767 | 15% | 2635 |
| 80-150 | 1231 | 1507 | 22% | 730 |
| 150 | 2549 | 2688 | 5% | 965 |
| ALL | 551 | 583 | 6% | 13562 |



# Imager IWC retrievals using profiling method agree well with in-situ aircraft data